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6. AUTHOR(S)

Prof. Robert G. Harrison

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Heriot-Watt University
Riccarton
Edinburgh EH14 4AS
United Kingdom

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1. **Nonlinear Dynamics of Semiconductor Lasers with External Feedback**
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6. Department of Physics, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK
7. Prof. Robert G Harrison Tel/Fax: 0131 451 3033, email: phyrgh@phyfsa.phy.hw.ac.uk

A. Abstract

This 6 months' contract concerns ongoing theoretical collaborative work between the Groups of Harrison and Gavrielides (Air Force Research Laboratory, Kirtland) on the nonlinear dynamics of external cavity semiconductor lasers, specifically low-frequency fluctuations and their synchronization properties.

B. Background

Over the last two decades, semiconductor lasers with external feedback have been successfully used for linewidth narrowing, suppression of secondary solitary modes and reduction of modulation-induced frequency chirp. However, under conditions of moderate feedback, these laser systems are well known to become dynamically unstable over broad operating conditions. One of the most prevalent forms of their dynamics are low frequency fluctuations (LFFs), and a current focus of high research activity. This phenomenon is characterised by sudden average power dropouts, followed by gradual buildup of the laser power. The successive dropouts occur on a slow time scale (nano- to microseconds), longer than characteristic times involved in the semiconductor laser dynamics, between which the power fluctuates on a fast time scale (tens of picoseconds). Such events are observed below and around the solitary laser threshold, over which range they become more frequent on increasing the pump rate. Though considerable progress has been made in their understanding, in both theory and experiment, central issues underlying the cause of this phenomenon remain unresolved. Specifically, the role of noise in generating LFFs, and the effect of multi-mode operation and noise on their dynamical nature are areas of continuing controversy in the field.

C. Results

1. Locked states, LFFs and the role of noise

There has been much debate on the nature of LFFs in the early literature - whether deterministic or stochastic. Until recently, the explanation has been focused on two major scenarios. The *theoretical* framework of the first is the commonly used *single-mode* analysis with or without noise, based on the Lang-Kobayashi (LK) equations - here we refer to mode content of the solitary laser (without feedback). Close to laser threshold and *without noise*, LFFs were explained as chaotic itinerancy with a drift among the chaotic ruins of the destabilised external cavity modes, in which dropouts are caused by collisions (crisis) of attractor ruins with anti-modes. Addition of noise does not affect their behaviour in this region. However, this deterministic view was challenged by recent spectrally-resolved *experimental* observations, showing that whenever LFFs occur, the lasers

operate in *multiple longitudinal modes* influenced by the spontaneous *noise*, thus putting into question the two earlier basic assumptions in the deterministic explanation, i.e., *single-mode* and *noise-free*. Further, recent statistical analysis of experimental measurements in the LFF regime gives evidence that LFFs are *stochastic* in nature.

This work has helped provide new insight on the role of noise in generating LFFs. A key finding is that at low noise levels, an initial LFF state evolves in time into a new low frequency periodic solution, referred to in our work as a *locked state*. For this state, the maximum laser power is locked to a harmonic of the external cavity frequency and the average power drops out *regularly* with a period of several (~10) external cavity round-trip times, within which pulsations occur on the fast time scale. The locked state has been obtained over operating conditions where the experimental LFFs were observed and shown to be weakly stable. Above the solitary laser threshold the periodic motion breaks into intermittency and then chaos on increasing pump current. Such features are preceded by long-lived transient LFF-type behaviour. We show that sustained LFFs may be falsely identified due to insufficient integration resolution and also the transient effect. With the inclusion of noise, the periodic behaviour is destroyed to a degree, depending on the relative strength of the noise to that of the laser signal. That is, large noise results in LFFs over the pump current range up to the solitary laser threshold while for smaller noise LFFs are only induced at lower currents and the emission otherwise retains its stable periodic behaviour up to this threshold. These new findings provide evidence that deterministic locked states underlie LFFs.

2. Effects of multi-longitudinal modes on low frequency fluctuations

Turning to the issue of single- versus multi-mode descriptions of LFFs, it is now increasingly clear from experiments that LFFs are a multi-mode phenomenon, not single-mode as commonly assumed in much of the earlier literature. With side modes suppressed to some extent, one longitudinal mode dominates, but a true single-mode operation is never achieved in experiments. In spite of this, the *single-mode* assumption in modelling has given surprisingly good qualitative agreement with experimental results. In this work, we further develop our theoretical analysis to describe multi-mode dynamics for comparison with our experimental findings. The model we used is a generalisation of the single-mode Lang-Kobayashi equations and multi-mode laser model often used for the solitary diode lasers. This model has been used successfully previously to analyse and evaluate the multi-mode intensity statistics obtained experimentally. This analysis considers the dynamical behaviours not only of the total intensity but also of a few frequency resolved dominant modes of the solitary laser. We find experimentally and numerically that the so-called locked state (Synchronous Sisyphus effect) in which the dropout events occur with a high degree of periodicity persists even when the laser operates on a large number of solitary cavity modes. Slow energy transfer between solitary modes is found to be a common effect when the laser undergoes LFFs or is in the locked state.

3. Phase synchronisation of LFFs

The synchronisation of coupled chaotic oscillators is currently a subject of active research since the pioneering work of Pecora and Caroll. Recently, a new phenomenon of phase synchronisation (PS) has been investigated in low-dimensional chaotic models and demonstrated on analog computer systems. Occurring in the synchronous regime, the phases of these coupled systems become entrained while their amplitudes remain uncorrelated. A generalisation of the synchronisation concept was considered in the investigation of a unidirectionally coupled system. In this study, the term, generalised synchronisation, was used when there exists a (static) functional relation between the states of two coupled systems. Following these developments, we may anticipate that, unlike the above cases of static functional relations, two coupled systems may be entrained only in some local regions in the phase space, or in certain time, but remain uncorrelated in the others. This type of

synchronisation was observed as intermittent synchronisation in coupled chaotic oscillators but has not been fully discussed.

In this work, we investigate through theory and experiment synchronisation in two unidirectionally coupled ECSLs. Our results show that the outputs of the master and slave lasers, both operated in the LFF regime, are synchronised in their sudden dropouts but their amplitudes on the fast scale remain strongly uncorrelated during recovery of their power. We have quantitatively characterised such motions by measuring the difference of the Hilbert phases of the two lasers on varying the coupling coefficient and pump current. In theory, a pair of coupled Lang-Kobayashi equations with inclusion of Langevin noise terms is used to describe the two external cavity semiconductor lasers, the results showing a good agreement with those from the experiment. We describe the observed phenomenon in terms of the different dynamical behaviour of the slave in the buildup and plateau regions in the phase space; the local unstable orbits are robust against perturbations in the former but more susceptible to intervention in the latter. These results provide evidence of the new phenomenon of synchronisation in local regions in phase space.

D. Publications

[1] Gavrielides, T.C. Newell, V. Konanis, R.G. Harrison, N. Swanston, Dejin Yu and W. Lu, "Synchronous Sisyphus effect in diode lasers subject to optical feedback", *Phys. Rev.* A **60**, 1577 (1999).

[2] Wallace, Dejin Yu, W. Lu and R.G. Harrison, "Experimental phase synchronisation of semiconductor lasers subject to optical feedback", *LEOS'99* (San Francisco USA, 1999).

[3] Wallace, Dejin Yu, W. Lu and R.G. Harrison, "Synchronization of power dropouts in coupled semiconductor lasers with external feedback", *Phys. Rev.* A (accepted, 2000).

[4] Wallace, Dejin Yu and R.G. Harrison, "Effect of noise on deterministic dynamics of semiconductor lasers subject to external optical feedback", *Phys. Rev.* A (Submitted, 2000)).

[5] Dejin Yu, I. Wallace, R.G. Harrison and A. Gavrielides, "Low frequency fluctuations in a multimode semiconductor laser with external cavity", *Phys. Rev.* A (Submitted, 2000)

[6] Wallace, Dejin Yu and R.G. Harrison, "Experimental observations of multi-mode dynamics in ECSL]{Experimental observations of multi-mode dynamics in an external cavity semiconductor laser", *Quantum & Semiclass. Opt.* (accepted, 2000)).

[7] R.G. Harrison, I. Wallace, Dejin Yu and W. Lu, " New insight into the nonlinear dynamics and synchronisation of external cavity semiconductor lasers", invited talk in *COCOS* (Munster Germany, 1999).